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Both midzone and astral microtubules are involved in the delivery of cytokinesis signals: insights from the mobility of aurora B

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To address the mechanism that coordinates cytokinesis with mitosis, we have studied the dynamics of aurora B, a chromosomal passenger protein involved in signaling cytokinesis. Photobleaching analyses indicated dynamic exchange of aurora B between a centromeric and a cytoplasmic pool before anaphase onset, and stable associations with microtubules after anaphase onset. Bleaching near centromeres upon anaphase onset affected the subsequent appearance of fluorescence along midzone microtubules, but not that near the lateral equatorial cortex, suggesting

that there were centromeric-dependent and -independent pathways that transported aurora B to the equator. The former delivered centromeric aurora B along midzone microtubules, whereas the latter delivered cytoplasmic aurora B along astral microtubules. We suggest that cultured cells use midzone microtubules as the primary signaling pathway for cytokinesis, whereas embryos, with their stockpile of cytoplasmic proteins and large sizes, rely primarily on astral microtubules.

Introduction

Cytokinesis is the final stage of cell division critical for the proper separation of chromosomes and organelles into two daughter cells. Despite much attention, it is still unclear how cytokinesis is coordinated with mitosis. Two major models have been raised for signaling cytokinesis (for reviews see Glotzer, 1997; Oegema and Mitchison, 1997; Glotzer, 2001; Wang, 2001). The first model contends that astral microtubules are primarily responsible for signaling cytokinesis. Its main evidence came from the classical study by Rappaport (1961), who demonstrated the formation of ectopic furrows between two adjacent mitotic spindles in micromanipulated sand dollar embryos. A similar study with artificially fused epithelial cells also found ectopic furrowing between neighboring spindles in a fraction of cells (Rieder et al., 1997). These experiments not only supported a model of stimulation based on overlapping astral microtubules (Rappaport, 1986; Devore et al., 1989; Harris and Gewalt, 1989), but also argued against a direct contribution of chromosomes to cytokinesis.

An equally compelling set of evidence suggests that chromosomes and midzone microtubules, which extend from separated

chromosomes toward the equatorial region during late mitosis, play a key role in signaling cytokinesis. For example, cytokinesis is inhibited by a perforation between the equatorial cortex and the spindle, even though the cortex has maintained its access to astral microtubules (Cao and Wang, 1996). In addition, under a number of experimental conditions, cortical ingression is correlated with the organization of midzone microtubules and their proximity to the cortex (Wheatley and Wang, 1996; Eckley et al., 1997; Giansanti et al., 1998). Treatment of cells with topoisomerase II inhibitors further revealed a set of microtubules that emanated laterally from the tangled chromosomes toward the cortex immediately before the ingression (Wheatley et al., 1998). These observations were corroborated by the discovery of a set of chromosomal passenger proteins, which relocate from centromeres to the equatorial region along midzone microtubules after anaphase onset (Martineau-Thuillier et al., 1998; Adams et al., 2001a). At least some of these proteins, including inner centromere protein (INCENP)* and aurora B, were essential for cytokinesis (Schumacher et al., 1998; Kaitna et al., 2000; Severson et al., 2000; Adams et al., 2001b; Giet and Glover, 2001; Levenson et al., 2002; Murata-Hori et al., 2002). However, although these experiments strongly sup-

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*Abbreviations used in this paper: INCENP, inner centromere protein; NRK, normal rat kidney.

Table I. Rate and extent of FRAP aurora B–GFP or the kinase inactive mutant of aurora B, aurora B(K-R)-GFP

	Slope	$t_{1/2}$	Recovery	n
	k	s	%	
Aurora B–GFP				
Prometaphase centromeres	-0.017 ± 0.007	47 ± 24	78 ± 13	13
Nocodazole centromeres	-0.013 ± 0.005	62 ± 19	59 ± 12	20
Aurora B(K-R)-GFP				
Prometaphase centromeres	-0.009 ± 0.003	84 ± 35	48 ± 14	13

The rate constant k was measured as the negative slope of $\ln(i_{\infty} - i_t)$ versus time after photobleaching. Halftime was calculated as $t_{1/2} = \ln 2 * (-1/k)$, as described in Materials and methods. Values are shown \pm SD.

port a signaling mechanism involving chromosomes and midzone microtubules, curiously ectopic furrows between mitotic spindles also contained a concentration of chromosomal passenger proteins (Savoian et al., 1999), suggesting that the process may be more complex than a simple transport of proteins from the centrosomes or centromeres to the equatorial cortex.

Critical insights into this puzzle may be gained by a detailed understanding of the dynamics of chromosomal passenger proteins. One of these proteins, aurora B, is known to play an essential role in both early and late stages of cell division, including chromosome congression, spindle checkpoint, chromosome segregation, and cytokinesis (Schumacher et al., 1998; Kaitna et al., 2000; Severson et al., 2000; Adams et al., 2001b; Giet and Glover, 2001; Kallio et al., 2002; Tanaka et al., 2002; Leversson et al., 2002; Murata-Hori and Wang, 2002; Murata-Hori et al., 2002). In the present study, we have applied FRAP, micromanipulation, and drug treatment to probe the dynamics of aurora B in dividing normal rat kidney (NRK) cells. Our data suggested that centromeric aurora B exchanges dynamically with a cytoplasmic pool during early mitosis. This exchange process stops upon anaphase onset, when centromeric aurora B becomes relocated to midzone microtubules and cytoplasmic aurora B is localized to astral microtubules. We further suggested that both pathways contribute to the signaling of cytokinesis, and that the differences in their relative contributions may explain the apparently conflicting views of cytokinesis signaling.

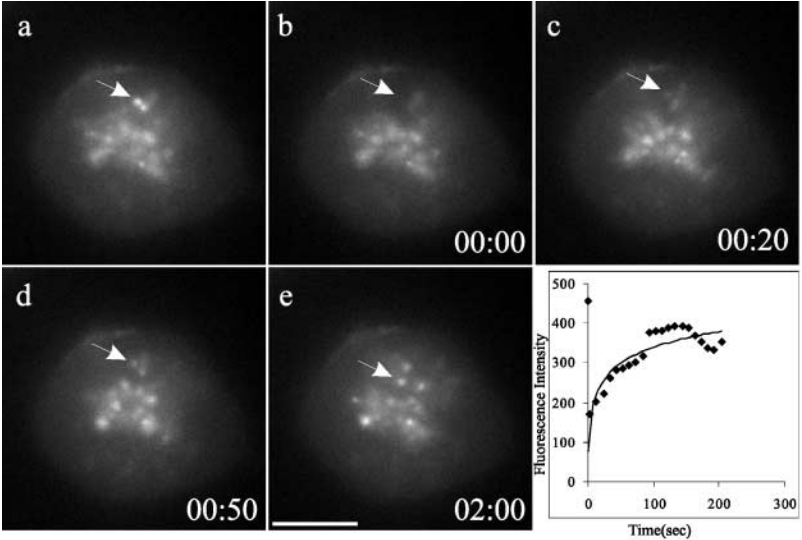
Results

Aurora B is a dynamic component of the centromere during early mitosis

We first applied FRAP analysis to investigate the mobility of aurora B at centromeres during prometaphase. Cells expressing aurora B fused to GFP (aurora B–GFP; Murata-Hori et al., 2002) were photobleached at centromeres with a small laser beam, and the recovery rate assessed from time-lapse images. The bleaching caused an $\sim 4\%$ decrease in total cellular fluorescence, with no detectable effect on mitosis or cytokinesis. As shown in Fig. 1 (Video 1, available at <http://www.jcb.org/cgi/content/full/jcb.200207014/DC1>), fluorescence returned to bleached centromeres with a relatively high rate ($t_{1/2} = 47 \pm 24$ s, $n = 13$) and extent (78%; Table I), indicating that most aurora B at centromeres was able to exchange with a noncentromeric pool. Similar results were obtained whether the bleached centromere was isolated or within a group of centromeres.

To assess if microtubules affect the turnover of aurora B at centromeres, we performed FRAP experiments after the disassembly of microtubules with 1 μ M nocodazole (Fig. 2 A; Video 2, available at <http://www.jcb.org/cgi/content/full/jcb.200207014/DC1>). The mobile fraction of centromeric aurora B decreased from 78% to 59%, and the turnover rate also decreased slightly from that in untreated cells ($t_{1/2} = 62 \pm 19$ s, $n = 20$; Table I). However, only the former was statistically significant ($P < 0.01$; Table I). We next asked if the turnover rate of aurora B was affected by its kinase activ-

Figure 1. FRAP analysis of aurora B–GFP turnover at centromeres of prometaphase cells. Fluorescence images of the cells were acquired before (a) and after (b–e) photobleaching a small number of centromeres (arrows). Time is shown in min:s. The fluorescence intensity gradually increased at bleached centromeres. Graphs show the fluorescence intensity at the indicated centromere. Bar, 10 μ m.



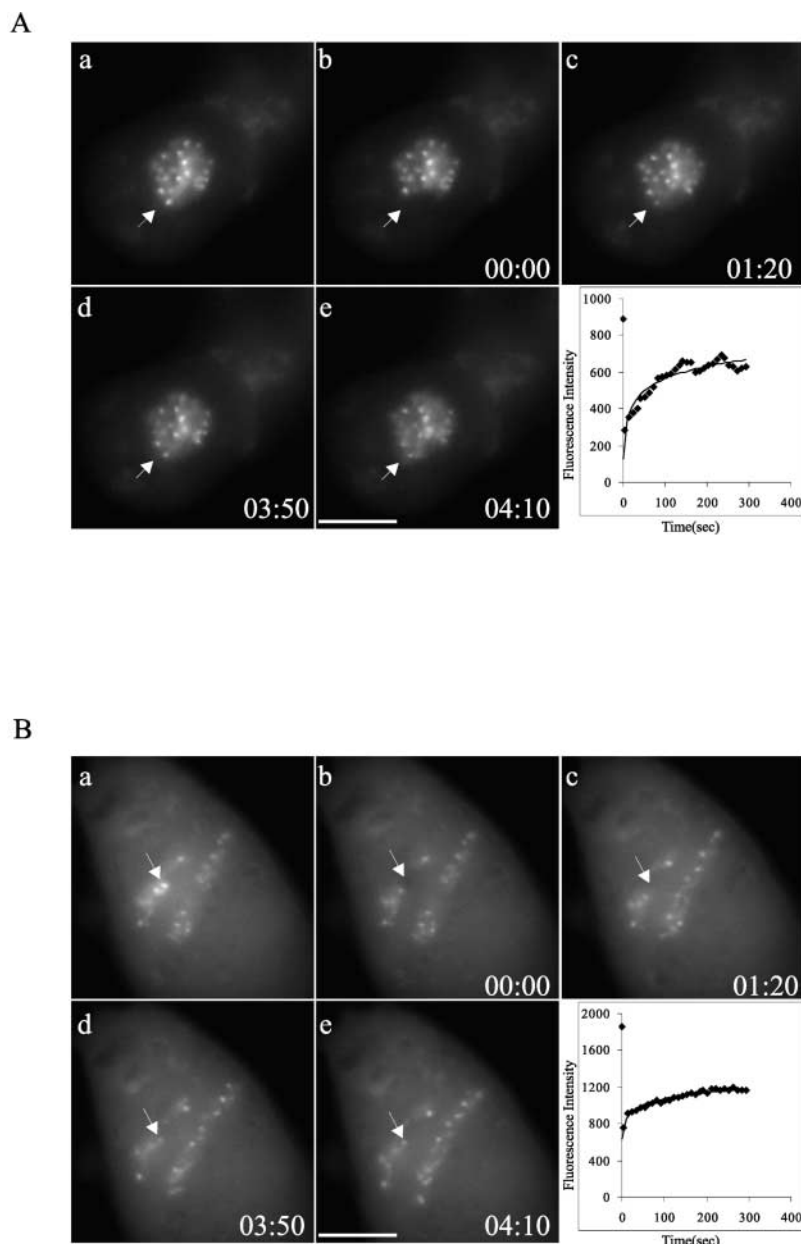


Figure 2. Effects of microtubule disassembly and kinase activity on the turnover of aurora B. (A) FRAP analysis of aurora B-GFP turnover at the centromeres of a nocodazole-treated mitotic cell. Cells expressing aurora B-GFP were treated with 1 μ M nocodazole for at least 3 h before the FRAP experiment. (B) FRAP analysis of kinase inactive aurora B(K-R)-GFP turnover at the centromeres of a prometaphase cell. Fluorescence images of the cells were acquired before (a) and after (b-e) photo-bleaching. Time is shown in min:s. Graphs show the time-course of fluorescence recovery at the indicated centromere (arrows). Bars, 10 μ m.

ity, which is essential for maintaining motor proteins on the kinetochores during prometaphase (Murata-Hori and Wang, 2002). FRAP analysis of GFP-tagged, kinase-inactive mutant of aurora B (aurora B[K-R]-GFP; Fig. 2 B; Video 3, available at <http://www.jcb.org/cgi/content/full/jcb.200207014/DC1>) at centromeres indicated a significant difference from wild-type aurora B-GFP in both the turnover rate ($t_{1/2}$ = 84 s vs. 47 s, $P < 0.01$; Table I), and the mobile fraction (48% vs. 78%, $P < 0.01$; Table I). These results suggested a limited dependence of the turnover of centromeric aurora B-GFP on microtubules and a stronger dependence on its kinase activity.

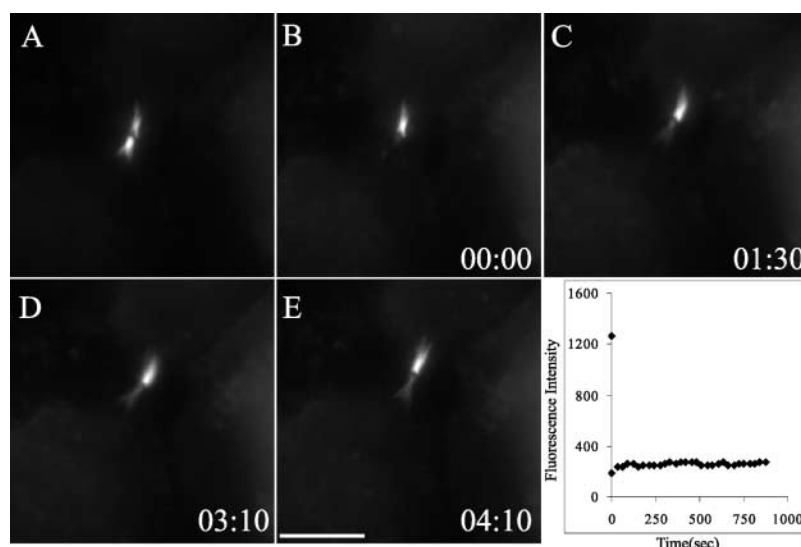
Aurora B shows a very slow turnover along midzone microtubules during late mitosis

Aurora B is known to relocate from centromeres to midzone microtubules after anaphase onset, and eventually to the midbody during telophase (Schumacher et al., 1998; Adams

et al., 2001b; Giet and Glover, 2001; Murata-Hori et al., 2002). To determine if aurora B underwent similar turnover at the midbody as at centromeres, we bleached half of the midbody with a small laser beam. As shown in Fig. 3 (Video 4, available at <http://www.jcb.org/cgi/content/full/jcb.200207014/DC1>), there was only a very limited recovery of aurora B-GFP in the bleached region, and a corresponding limited loss of fluorescence in the unbleached region, during the period of observation. In both regions the rate of change was too low for a reliable measurement of the halftime. These results suggested that aurora B was stably associated with the midbody.

The turnover rate of aurora B during anaphase was more difficult to measure, due to the rapid, extensive reorganization of spindle structures and the relocation of chromosomal passenger proteins. Therefore, we performed bleaching immediately after anaphase onset, when most aurora B in the equatorial region was still localized either at centromeres or

Figure 3. Stable association of aurora B at the midbody. Fluorescence images of the cells were acquired before (A) and after (B–E) photobleaching half of the midbody in a cell expressing aurora B–GFP. Time is shown in min:s. The graph shows a very slow increase of fluorescence intensity in the bleached region. Conversely, the unbleached half shows no appreciable decrease in fluorescence intensity. Bar, 10 μ m.



along adjacent midzone microtubules. This allowed us to bleach nearly all aurora B at or near centromeres with a large laser beam, and to ask if midzone microtubules subsequently became fluorescent as in nonbleached cells. The bleaching caused an $\sim 30\%$ decrease in total cellular fluorescence; however, diffuse, cytoplasmic fluorescence returned to the bleached region within 10 s. As shown in Fig. 4 (Video 5, available at <http://www.jcb.org/cgi/content/full/jcb.200207014/DC1>), except for the region near the lateral equatorial cortex (discussed below), no bright fluorescent structures were subsequently found in the equatorial region at the onset of cytokinesis. This was in contrast to the striking concentration of fluorescence along the array of midzone microtubules seen in unbleached cells ($n = 20$; Fig. 4, C and C'). The extent of equatorial localization remained much lower in bleached cells than that in unbleached cells throughout cytokinesis over a period of 5 min (Fig. 4, D and D'). Furthermore, when aurora B–GFP was partially bleached around centromeres, reduced fluorescence was found along the corresponding portion of midzone microtubules during cytokinesis (unpublished data). Together, these results suggest that aurora B relocated directly from centromeres to midzone microtubules with a very limited turnover.

Cytoplasmic aurora B is transported to the equatorial cortex along astral microtubules

Surprisingly, despite the extensive bleaching of fluorescence at central equatorial region, and the large decrease of aurora B–GFP fluorescence along midzone microtubules in the previous experiment, concentration of aurora B–GFP developed near the lateral equatorial cortex (Fig. 4, C and D, arrows), suggesting that there might be a centromere-independent pathway that delivered cytoplasmic aurora B to the equatorial cortex. To determine if astral microtubules played a role in this process, NRK cells expressing aurora B–GFP were treated with a low dose of nocodazole (150 nM), which causes a preferential disassembly of astral microtubules (O'Connell and Wang, 2000). Compared with control cells (Fig. 5 A, right), nocodazole-treated cells showed a pronounced reduction of aurora B along the lateral equatorial cortex (Fig. 5 A, left),

whereas midzone microtubules maintained a strong accumulation of aurora B (Fig. 5 A, right; Murata-Hori et al., 2002).

As an alternative approach, a perforation was generated between the central spindle and the equatorial cortex (Fig. 5 B). As was shown previously (Cao and Wang, 1996), the region between the perforation and the lateral cortex contained only astral microtubules. Immunofluorescence staining of aurora B indicated a small but detectable amount of aurora B along the cortex of this region (4/5, Fig. 5 B, inset), suggesting that astral microtubules were able to mediate the transport of a minor fraction of aurora B to the equatorial cortex.

Both midzone and astral microtubules contribute to the signaling of cytokinesis

To determine the functional role of astral microtubules in cytokinesis, we examined the cytokinesis of cells treated with 150 nM nocodazole to disassemble preferentially astral microtubules as described above. As reported previously, these cells showed a high frequency of mispositioned spindles (O'Connell and Wang, 2000). We found that cytokinesis became highly asymmetric when the spindle was located closer to one side of the lateral cortex than the other side by $>50\%$ (Fig. 6 A). Deep ingression occurred on the side with a short distance, whereas no ingression or shallow ingression took place on the other side (77%, $n = 13$). Thus, midzone microtubules by themselves were not able to signal cytokinesis over a long distance, and astral microtubules were likely involved in the early phase of cytokinesis before the cortex was brought near the spindle by the ingression. However, astral microtubules by themselves were insufficient for stimulating cortical ingression in NRK cells, as indicated by the previous observation that a perforation imposed between the cortex and the spindle blocks local ingression despite the presence of astral microtubules and some aurora B in the region (0/9, Fig. 5 B; Video 6, available at <http://www.jcb.org/cgi/content/full/jcb.200207014/DC1>; Cao and Wang, 1996).

To test the possibility that the effectiveness of astral microtubules in stimulating cytokinesis is determined by the amount of aurora B delivered by these microtubules, we performed the perforation experiment with cells expressing a

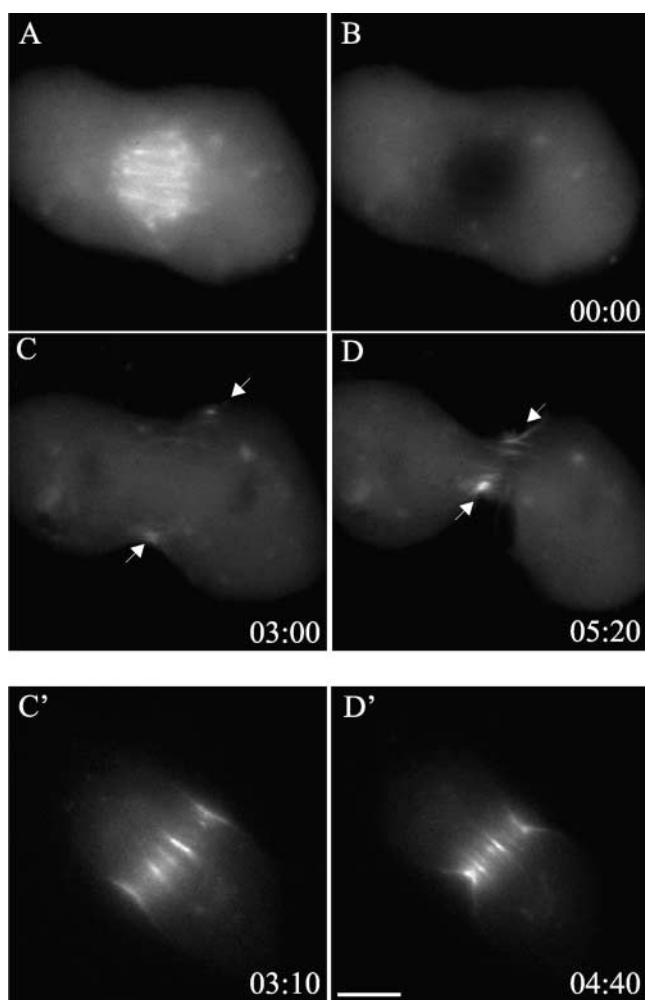


Figure 4. Photobleaching of aurora B-GFP during anaphase. A large laser beam was used to bleach aurora B-GFP around centromeres at early anaphase. Fluorescence images were acquired before (A) and after (B–D) photobleaching. Few fluorescent structures emerged in the spindle midzone (C and D), whereas strong fluorescence was observed along the midzone microtubules in a nonbleached cell (C' and D'). Concentration of aurora B-GFP was observed primarily along the lateral edges of the equatorial region despite the bleaching (C and D, arrows). Time after the anaphase onset is shown in min:s. Bar, 10 μ m.

high level of aurora B-GFP (Fig. 6 B). In contrast to non-transfected cells (Fig. 5 B), these cells showed a variable degree of ingress along the equatorial cortex blocked from the spindle (15/18, Figs. 6 B, arrow, and S1; Video 7, available at <http://www.jcb.org/cgi/content/full/jcb.200207014/DC1>). Immunofluorescence confirmed the presence of a larger amount of aurora B along the cortex than in untransfected cells (Fig. 6 B). Together, these experiments indicate that both astral and midzone microtubules played a role in signaling cytokinesis.

Discussion

Dynamics of aurora B during early mitosis

Previous studies have demonstrated an essential role of aurora B and other chromosomal passenger proteins in signal-

ing cytokinesis. These proteins are localized at centromeres in early mitosis, and along midzone microtubules during late mitosis (Adams et al., 2001a). Thus, the simplest model for the stimulation of cytokinesis would involve a transport mechanism, which delivers these proteins from centromeres to the equatorial cortex along midzone microtubules. However, although this model provides a plausible explanation for the spatial and temporal coordination of cytokinesis with mitosis, it does not easily explain the observations that convincingly demonstrated the involvement of astral microtubules (Rappaport, 1961; Rieder et al., 1997).

A more comprehensive understanding of this signaling process may be achieved through a better characterization of the behavior of the chromosomal passenger proteins during various stages of cell division. In the present study, we have applied a combination of FRAP, drug treatment and micro-manipulation to study the dynamics of aurora B. The first significant finding is that aurora B, and likely other chromosomal passenger proteins, is not a stable passenger of the chromosomes, but constantly hops on and off centromeres prior to anaphase onset. Moreover, because the turnover rate is not significantly affected by the disassembly of microtubules, the process likely involves a cytoplasmic pool that interacts directly with the centromeres.

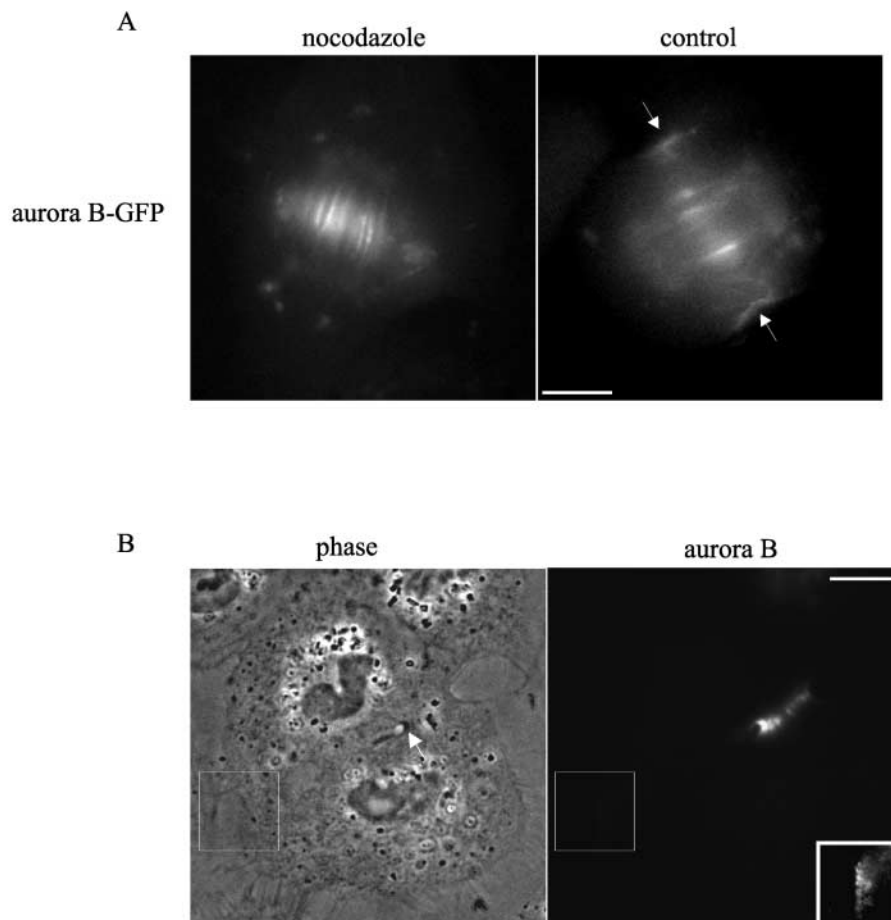
The half recovery time of aurora B at centromeres, 47 ± 24 s, was not drastically different from that of the checkpoint protein Mad2 (~ 24 –28 s; Howell et al., 2000). Moreover, nocodazole had a similar detectable effect on the mobile fraction of both proteins at centromeres (Howell et al., 2000). The similar behavior of aurora B and Mad2 during prometaphase raises the possibility that checkpoint proteins and chromosomal passenger proteins may form a complex during early stages of mitosis. A mechanism linked to the spindle checkpoint may maintain the integrity of the complex and keep aurora B from associating with microtubules upon anaphase onset. Consistent with this idea, we found that the kinase activity of aurora B is involved in maintaining the binding of Mad2 and microtubule motor proteins at prometaphase kinetochores (Murata-Hori and Wang, 2002; Murata-Hori et al., 2002). In addition, the possibility of a kinase-regulated complex is supported by the dependence of the mobility of aurora B on its kinase activity (Table I), and by the dependence of Mad2 turnover on ATP (Howell et al., 2000).

Dynamics of aurora B during late mitosis and cytokinesis

Upon anaphase onset, aurora B is transferred from centromeres to midzone microtubules. The concentration and limited turnover of fluorescence at the midbody suggested a change from dynamic association at centromeres, to stable association with a highly possessive motor that migrated along microtubules to the midbody. However, the most interesting finding was the identification of two discrete pathways that deliver aurora B to the equatorial region. First, bleaching of aurora B-GFP at central equatorial region during early anaphase caused a strong reduction in the subsequent concentration of fluorescence along midzone microtubules. The observation is most easily explained by a direct relocation of centromeric aurora B to midzone microtubules during early anaphase, coupled to a limited exchange of

Figure 5. Transport of cytoplasmic aurora B to the equatorial cortex along astral microtubules.

(A) Cells expressing aurora B–GFP were treated with 150 nM nocodazole for at least 3 h. Aurora B–GFP was observed along midzone microtubules but not the lateral equatorial cortex in treated cells, while it was localized along both structures in control cells (arrows). (B) Immunofluorescence of endogenous aurora B after cell perforation (arrow). The perforation, positioned near the left edge of the metaphase plate, caused inhibition of cytokinesis on the side blocked from the mitotic spindle (boxed region). The perforation migrated toward the upper right as a result of biased ingression activities (arrow; Cao and Wang, 1996). The cell was subsequently fixed and stained with anti–aurora B antibodies. Most aurora B was detected on the cleaving side. However, very faint staining of aurora B was observed along the cortex of the perforated side upon enhancement of the image (inset). Bars, 10 μ m.



microtubule-associated aurora B with cytoplasmic aurora B–GFP. However, some fluorescent aurora B did appear near the lateral equatorial cortex despite the extensive bleaching of the equatorial region at early anaphase. Although it is difficult to rule out the contributions from residual unbleached aurora B, or from a very slow exchange between microtubule-associated and cytoplasmic aurora B, we noticed that the distribution of fluorescent structures is biased toward the lateral edges of the cell. This suggests that the fluorescence was associated with a subset of microtubules and that there may be a second mechanism that delivered noncentromeric aurora B to the equator.

Our results corroborate the previous finding that a number of chromosomal passenger proteins showed discrete localizations both on the lateral equatorial cortex and along midzone microtubules during anaphase, whereas some kinetochore proteins such as CENP-E were found only along midzone microtubules (Martineau-Thuillier et al., 1998). The inhibition of lateral cortical localization by low doses of nocodazole, and the insensitivity of such localization to cell perforation, further suggests that the transport of this fraction of aurora B involves primarily astral microtubules. These microtubules reach various regions of the dividing cell: some concentrated directly onto the equatorial cortex whereas others are incorporated into midzone microtubule bundles near the equatorial cortex. This explains the curious pattern of fluorescence seen during early and late cytokinesis after the equatorial region was bleached with a large laser beam (Fig. 4 D).

Therefore, the most plausible explanation is that the cytoplasmic pool of aurora B, which is involved in the exchange with the centromeric pool during prometaphase, is recruited preferentially to astral microtubules after anaphase onset and subsequently transported to the cortex by a similar mechanism that transports centromeric aurora B along midzone microtubules. The preferential recruitment of cytoplasmic aurora B to astral microtubules implies that midzone microtubules may differ qualitatively from astral microtubules, as suggested also by their differential sensitivity to nocodazole (Wheatley and Wang, 1996; O'Connell and Wang, 2000). Alternatively, the localization to astral microtubules may require specific entry points such as the spindle pole.

Signaling of cytokinesis in animal cells

We suggest that there are two mechanisms that deliver cleavage signals to the equatorial cortex. The first mechanism is mediated by cytoplasmic aurora B and astral microtubules. It functions primarily during the early stage of cytokinesis, before the cortex is brought to the vicinity of the mitotic spindle by ingression. In addition, it is capable of delivering the signal not only to the equator but also to other regions accessible to astral microtubules, including the polar cortex. Thus, this mechanism is responsible for the ectopic furrowing between two adjacent mitotic spindles, as seen in the experiments of Rappaport (1961) and Rieder et al. (1997). The second mechanism is mediated by centromeric aurora B and midzone microtubules. It

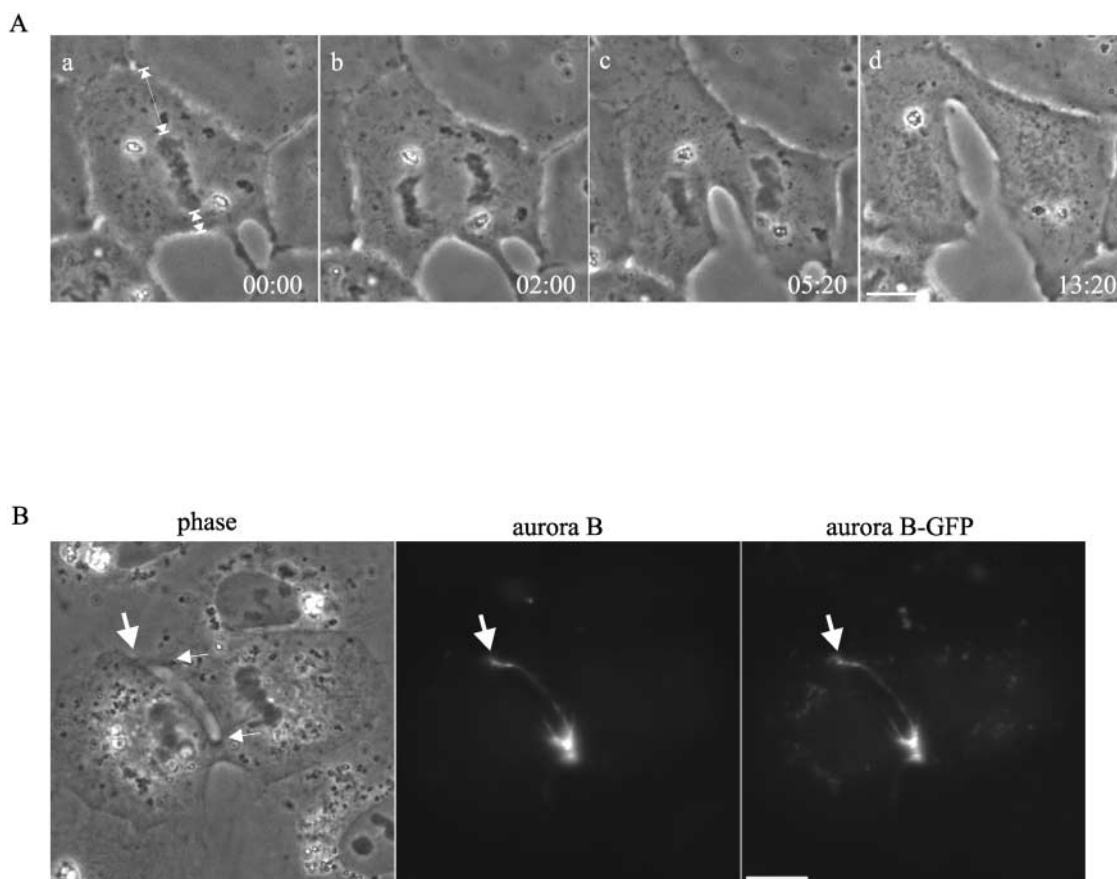


Figure 6. **Involvement of both astral and midzone microtubules in signaling cytokinesis.** (A) Cells were treated with 150 nM nocodazole (a–d) for at least 3 h before observation. Nocodazole caused spindle mispositioning, and unequal distances between the spindle and the two lateral edges of the equator (a). The side located further from the mitotic spindle failed to ingress (a–d). (B) Perforation was performed in a metaphase cell expressing a large amount of aurora B–GFP. The side blocked from the spindle is indicated by large arrows. Cytokinesis occurred on both sides of the perforation, causing the perforation to extend into a wide slit (small arrows). Concentration of aurora B was detected with immunofluorescence (middle) and GFP (right) along both sides of the perforation (compare with Fig. 5 B). Bars, 10 μ m.

is located in the more interior of the cell and functions primarily during the late stage and completion of cytokinesis.

The relative contribution of the two pathways likely varies among different cell types. In NRK cells, the astral microtubule pathway delivers only a limited amount of aurora B to the cortex, and is insufficient for stimulating cytokinesis as indicated by the failure of ingression in perforated cells. However, it plays a synergistic role with the midzone microtubule pathway and becomes increasingly important as the spindle is further separated from the cortex, as indicated by the experiments with low dose nocodazole. This mechanism also explains the somewhat equivocal role of centrosomes in cytokinesis, as suggested by an increased failure in cytokinesis upon the ablation of centrosomes (Khodjakov and Rieder, 2001).

The contribution of the astral microtubule versus midzone microtubule pathway is likely determined by the relative amount of centromeric and cytoplasmic aurora B at anaphase onset, the length of astral microtubules, and the distance between the spindle and the cortex. We found that the effect of astral microtubule pathway increased with the level of expression of aurora B in NRK cells, eventually overcoming the inhibitory effect of perforation. This pathway likely plays a major role in early embryos, where aurora B

may exist in stockpiles and the spindle is separated from the cortex by up to several hundred microns.

Although our results readily reconcile the two apparently conflicting models of cytokinesis, many important questions remain. Of prime importance is the mechanism that regulates the localization and dynamics of aurora B at early anaphase, and the mechanism that transports aurora B to the cortex. Equally important are the targets of aurora B both before and after anaphase onset. The diverse effects of the disruption of aurora B suggest that there are multiple targets at various structures including centromeres and the cortex. Moreover, as an increase in aurora B is sufficient to overcome the inhibitory effect of perforation, it is reasonable to assume that aurora B indeed represents a key component in the signaling mechanism of cytokinesis.

Materials and methods

Cell culture, microscopy, and image processing

NRK epithelial cells (NRK-52E; American Type Culture Collection) were cultured in Kaighn's modified F12 (F12K) medium supplemented with 10% FBS (JRH Bioscience), 50 U/ml penicillin, and 50 μ g/ml streptomycin, on glass chamber dishes as previously described (McKenna and Wang, 1989). The cells were maintained at 37°C in a stage incubator built on top of a Zeiss Axiovert S100TV or an Axiovert 35 inverted microscope,

and viewed with a 100 \times , NA 1.30 Fluor lens or 40 \times , NA 0.75 Fluor lens. All images were acquired with a cooled charge-coupled device camera (ST133 controller and CCD57 chip; Roper Scientific) and processed with custom software for background subtraction.

Transfection, drug treatment, and micromanipulation of the cells

NRK cells were plated on a coverslip chamber dish and incubated for 18–24 h. Immediately before transfection, the cells were rinsed once in Opti-MEM I medium (Life Technologies). The cells were transfected with the DNA constructs (1 to 2 μ g) using LipofectAMINE according to manufacturer's instructions (Life Technologies). After 4 h incubation, the medium containing DNA-LipofectAMINE was replaced with the F12K medium containing 10% FBS, and the cells were cultured for an additional 14–16 h. Nocodazole (Sigma-Aldrich) was stored at -20°C as $10^3\times$ stocks in DMSO and diluted into prewarmed medium before application to cells. Cell perforation was performed as described previously (Cao and Wang, 1996).

Laser photobleaching and data analysis

Photobleaching experiments were performed with 476.5 nm Argon ion laser at 50 mW for bleaching small areas, or 200 mW for bleaching large areas. The laser beam was passed through a combined spatial filter–beam expander (Newport Corp.) and was focused with an $f = 475$ mm plano-convex lens (Optics for Research) to the plane of the epi-illuminator field diaphragm of a Zeiss Axiovert 35 microscope. All bleaching experiments were performed with a 100 \times , NA 1.30 Fluor lens and with 50-ms laser pulses. The size of the laser beam was controlled by moving the exit lens of the spatial filter–beam expander. The full-width half-maximal size of the laser beam on the objective plane, measured by imaging the attenuated beam with a thin layer of fluorescent solution, was 0.6 μ m for small beams and 5.7 μ m for large beams. The actual size of the bleached region was measured by dividing the images of the cell immediately before and after bleaching, and determining the diameter where the ratio drops by 50%. The small beam typically created a bleached region 4.3 μ m in diameter, whereas the large beam created a spot 11.1 μ m in diameter.

A mirror mounted on a computer-controlled, rotating wheel controlled the entry of laser versus the illumination beam from an attenuated 103W mercury arc lamp into the microscope. The computer, with custom programs, also controlled the acquisition of images before and after bleaching. The dichroic mirror and emission filter for the epi-illuminator were from a Chroma Technology 51004 v2 SBX double-band filter set for fluorescein and tetramethylrhodamine. The excitation filter was a 490 nm, 7.3-nm band-pass filter (Coherent Ealing), mounted with a BG-38 heat filter in front of the arc lamp. Images of fluorescence recovery were captured every 5–30 s. The measurement of the fluorescence intensity was performed with custom software. Because the image acquisition process caused no significant fluorescence photobleaching ($\sim 3\%$ over the period of acquisition), the images were corrected only for the camera background.

The turnover rate was determined by plotting $\ln(i_{\infty} - i_t)$ versus time, where i_{∞} is the fluorescence intensity in the bleached area at time infinity and i_t is the fluorescence intensity at time t . The rate constant k was measured as the negative slope of the plot and the half-time was calculated as $t_{1/2} = \ln 2 * (-1/k)$. The percent mobile fraction was calculated from i_{∞} , the intensity immediately after bleaching i_0 , and the prebleaching fluorescence intensity i_{pre} : $100\%[(i_{\infty} - i_0)/(i_{pre} - i_0)]$. The value of i_0 was calculated by extrapolating the plot of $\ln(i_{\infty} - i_t)$ versus t to $t = 0$. The significance of the results was assessed using analysis of variance and Student's t test in Microsoft Excel.

Immunofluorescence

Cells were rinsed with warm cytoskeleton buffer and fixed with 4% paraformaldehyde (EM Science) in warm cytoskeleton buffer for 10 min (Wheatley and Wang, 1996). They were then rinsed thoroughly in the cytoskeleton buffer and permeabilized by incubation with 0.5% Triton X-100 in cytoskeleton buffer for 5 min. Fixed cells were rinsed with the cytoskeleton buffer, blocked for 10 min with 1% BSA (Boehringer Mannheim) in PBS, and then incubated with anti-AIM-1 monoclonal antibodies (Murata-Hori et al., 2000, 2002) at a dilution of 1:100 in PBS with 1% BSA for 45 min at 37°C . After washing with PBS/BSA thoroughly, the cells were incubated with Alexa 546-conjugated goat anti-mouse antibodies (Molecular Probes) at a dilution of 1:100 for 30 min at 37°C .

Online supplemental material

Videos of fluorescence images corresponding to Figs. 1–4 (Videos 1–4) and 5 B (Video 5), Fig. S1 (Video 6), and a video recorded under the same

condition as that for Fig. 6 B (Video 7), are available at <http://www.jcb.org/cgi/content/full/jcb.200207014/DC1>.

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